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STRESS-WAVE PROPAGATION IN ALUMINUM

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STRESS-WAVE PROPAGATION IN ALUMINUM

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ABSTRACT: The one-dimensional theory of stress-wave propagation has been found to adequately represent a three dimensional experimental situation in both the elastic and plastic regimes. An air gun was used to accelerate a rod and impact it against a stationary test rod to produce a force pulse. The strain resulting from this pulse was recorded at various positions along the test rod. The deviation between the theoretical and experimental values of maximum stress was less than 11.5 percent.

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WHITE OAK, MARYLAND

STRESS-WAVE PROPAGATION IN ALUMINUM

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The authors wish to express their appreciation to Drs. A. E. Seigel and V. C. D. Dawson for their valuable contributions to this program.

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A. E. Seigel
A. E. SEIGEL
By direction

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ILLUSTRATIONS

LIST OF SYMBOLS

a Lagrangian length coordinate

f Function

g Shift rate defined by equation 5

t Time

u Particle velocity

A Cross-sectional area

E Young's modulus

I Impedance

K Constant defined by equation 15

ϵ Strain

ρ Initial mass density

σ Stress

ϕ Impact velocity defined by equation 6

INTRODUCTION

The impact of a re-entry body during either water entry or hard surface landing operations produces very severe loads in the structure. When the body first strikes the target, a compressive stress wave emanates from the surface of contact often causing damage to the payload. It becomes necessary to mitigate the loads felt by the payload so that the maximum allowable stress is not exceeded.

One possible method of protecting the payload is to make use of the cancellation of high-intensity plastic stress waves by faster traveling elastic unloading stress waves. The work reported here was undertaken as a result of an idea proposed by Drs. A. E. Seigel and V. C. D. Dawson as a method of mitigating shocks experienced by re-entry vehicles. The basic concept is discussed in a report (in preparation) by Drs. Seigel and Dawson.

In an effort to verify the theory of stress-wave cancellation, it was desired to compare the results of experimental tests with calculations using the one-dimensional theory of stress-wave propagation. The structure used for this study was a simple free-ended test rod. To simulate loads obtained from impact, a rectangular force pulse was suddenly applied to the test rod by impacting a second rod against it. The problem considered is therefore that of predicting the stress-time history at any point in the test rod and comparing it to experimentally measured values.

THEORETICAL CONSIDERATIONS

The theory studied in this investigation has been derived by numerous investigators, the first being Th. von Karman (ref. (1)) and G. I. Taylor (ref. (2)). It is a one-dimensional theory applicable to both elastic and plastic wave propagation.

For simplicity, only strain rate independent materials have been considered here so that stress is a function of strain only:

$$\begin{aligned} \sigma &= E\epsilon & 0<\sigma<\sigma_Y \\ \sigma &= f(\epsilon) & \sigma \geqslant \sigma_Y \end{aligned} \qquad (1)$$

The behavior of the rod is governed by the equations of continuity and momentum which take the following form in the Lagrangian coordinate system:

$$\frac{\partial u}{\partial a} = \frac{\partial \epsilon}{\partial t} \qquad (2)$$

$$\frac{\partial \sigma}{\partial a} = \rho_0 \frac{\partial u}{\partial t} \qquad (3)$$

Introducing the shift rate, g, and impact velocity, ϕ, the above equations may be rewritten in the following form:

$$\frac{\partial}{\partial t}(u \pm \phi) \mp g \frac{\partial}{\partial a}(u \pm \phi) = 0 \qquad (4)$$

where $$g^2 = \frac{1}{\rho_0} \frac{d\sigma}{d\epsilon} \qquad (5)$$

and $$d\phi = g\, d\epsilon = \frac{1}{\rho_0 g} d\sigma \qquad (6)$$

In the experiments reported here, 7075-0 aluminum was used exclusively for the test rod since it does not exhibit an appreciable strain-rate dependence at room temperature (ref. (3)). The static stress-strain relationship for this material is shown as figure 1.* Equations (5) and (6) have been used to determine the shift rate and impact velocity as a function of stress, and are shown in figures 2 and 3.

As previously stated, a rectangular force pulse was generated in the test rod by the impact of a second rod traveling at constant velocity. In order to obtain a rectangular force pulse, it will be shown that the impacting rod must necessarily remain elastic and have an impedance, $I = \rho g A$, equal to or less than that of the test rod. To attain these requirements the impacting rods were made of high-strength magnesium or 7075 aluminum alloy, heat treated to the "-T6" condition while the test rods were made of 7075 aluminum alloy in the annealed, or "-0," condition. The higher strength impacting rods could thus be made to remain elastic during impact while the test rods deformed plastically.

Figure 4 shows the two rods and the resulting characteristic net in the a-t plane for a case where plastic deformation

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* This stress-strain curve was obtained experimentally by the authors. Specimens 0.500-inch dia. and 0.750-inch long were instrumented with post-yield type strain gages and loaded compressively with a standard testing machine.

takes place. The initial conditions are (subscripts indicate regions in fig. 4):

$$\left.\begin{array}{l} u_A = 0 \\ \phi_A = 0 \end{array}\right\} \qquad \text{test rod} \qquad (7)$$

$$\left.\begin{array}{l} u_B = -u_o \\ \phi = 0 \end{array}\right\} \qquad \text{impacting rod} \qquad (8)$$

From equation (4), it may be said that

$$u_D - \phi_D = u_A - \phi_A$$

Therefore, from equation (7)

$$u_D - \phi_D = 0 \qquad (9)$$

Likewise, from equation (4) it may be said that

$$u_c + \phi_c = u_B + \phi_B$$

Therefore, from equation (8)

$$u_c + \phi_c = -u_o \qquad (10)$$

If the two rods have the same cross-sectional area, then

$$\sigma_c = \sigma_D \qquad (11)$$

and

$$u_c = u_D \qquad (12)$$

Combining equations (9), (10) and (12) yields

$$\phi_D + \phi_c = -u_o \qquad (13)$$

The quantity ϕ_c is the impact velocity of the impacting rod, which may be found from equation (6) if it is assumed that the bar remains elastic so that the shift rate remains constant. This quantity has been calculated for 7075-T6 aluminum alloy and ZK60A magnesium alloy and is shown in figure 2. Equations (11) and (13) may be solved graphically by adding the impact velocities plotted in figure 3 to obtain σ_c as a function of the initial velocity as shown in figure 5.

The stress at any point between regions A and D in figure 4 may be calculated by the following method:

$$u_p - \phi_p = u_A - \phi_A = 0 \tag{14}$$

$$u_p + \phi_p = K \tag{15}$$

where K is a constant associated with each characteristic line. Solving equations (14) and (15) simultaneously we obtain:

$$u_p = \phi_p = \frac{1}{2} K \tag{16}$$

The stress may be obtained directly from figure 3 for each value of K.

As the unloading wave penetrates the test rod, the material will obey the elastic stress-strain relation. Therefore, the characteristic lines of slope "-g" intersect causing a discontinuity in properties which may only be resolved by the formation of a shockwave. The shock equation relating regions D and E are:

$$\frac{\Delta \sigma}{\Delta u} = -\rho_o g_E \tag{17}$$

and

$$\frac{\Delta \sigma}{\Delta \epsilon} = E \tag{18}$$

where the subscript E indicates the elastic shift rate. When the above equations are used in conjunction with the method of characteristics it may be shown that:

$$\sigma_E = \sigma_D \frac{I_I - I_T}{I_I + I_T} \qquad \text{for} \quad I_I \geq I_T \qquad (19)$$

and $\quad \sigma_E = 0 \qquad$ for $\quad I_I \leq I_T$

where I is the aforementioned impedance, $\rho g A$, and the subscripts I and T refer to the impacting and test rods, respectively. These equations are valid for elastic or plastic deformation of the test rod, provided that the impacting rod remains elastic.

From the first of equations (19), it can be seen that a zero-stress condition will result if $I_I = I_T$ (as in the case of impact of aluminum on aluminum), producing the rectangular pulse desired. If I_I is less than I_T (as in the case of magnesium impacting aluminum), the first of equations (19) indicates tension; since this is not possible, the two rods will separate producing a similar zero-stress condition. In either of these two cases, the characteristic line separating regions F and F' does not exist.

In the plastic case, the shockwave separating regions D and E penetrates rod I until the change in stress across the wave is zero. This creates two regions, G and H shown in figure 4, of constant stress but having different strain histories. The material associated with regions E and G has already been loaded into the plastic regime and then unloaded along an elastic curve. The material associated with region H has not yet been unloaded so that σ_H is the maximum stress occurring at that time.

The method of calculation used here is a relatively easy method of determining the elastic and plastic stress-time history anywhere in an impacted material provided: (1) the loading pulse, force-versus-time, is rectangular or a small number of constant stress levels, and (2) the stress occuring after the first unloading wave in the plastic case is not needed. This later history in some plastic cases includes a "secondary plastic region" (ref. (4)). This region is short in length along the bar, occurring near the boundary between the primary plastic and elastic regions. The method of calculation presented here is not readily adaptable to the determination of the boundaries of this region as six significant figures would have to be carried for the required accuracy. However, the experimental test indicated that the stresses in the secondary plastic regions were always less than those in the primary regions for which calculations were made.

EXPERIMENTAL TEST APPARATUS

The impacting and test rods used in the experiments were 0.500 inch in diameter. The impacting rods were 12 inches long which produced a loading pulse of approximately 120 microseconds, the time required for a stress wave to travel down the rod and back. In the all-elastic tests, the test rod was 144 inches in length; in the plastic test, the test rods were approximately 40 inches in length.

An air gun, shown schematically in figure 6, was used to accelerate the bore size impacting rod. In operation, a mylar diaphragm was placed between the gun's high-pressure chamber and barrel. Air was loaded into the chamber until the diaphragm burst, sending the impacting bar down the barrel. Velocity of impact was controlled by varying the diaphragm thickness and the initial distance between the diaphragm and impacting rod. Vent holes were put in the end of the gun barrel to relieve the driving pressure before impact. The velocity of impact was measured by two photoelectric units connected to a time-interval counter which was operated when light beams passing through holes drilled in the end of the barrel were interrupted by the impacting rod.

The test rod was inserted into the end of the gun barrel to assure normal impact of the rods. This rod was instrumented with a pair of strain gages at each of six points along the length of the rod for the plastic case and two points for the all-elastic case. The strain gages in each pair were mounted 180° to one another and connected into a Wheatstone bridge in an additive manner so that any bending strains in the rod would cancel out. The outputs from the Wheatstone bridges were fed into oscilloscopes equipped with cameras for photographing the displays. The oscilloscopes were connected to trigger together, with the first oscilloscope set to trigger on the incident stress wave. Baldwin type FAB 12-12 strain gages were used in the tests when the strain was all elastic, and PA-7 gages were used where plastic strains occurred. Typical oscilloscope traces are reproduced in figure 7. A marker generator was connected to the oscilloscopes to blank the trace every 50 microseconds. The calibration traces were obtained by switching a resistor of known value in parallel with one arm of the Wheatstone bridge.

EXPERIMENTAL DATA REDUCTION

The oscilloscope traces were reduced to stress-time curves in the following way. The value of strain represented by the calibration trace was calculated from the manufacturer's gage

factor. The Wheatstone bridge outputs were then read from the oscilloscope photographs making use of a comparator and reduced to strain making use of the calibration. Reduction to stress was achieved using the stress-strain curve shown in figure 1, always following an elastic line during unloading and reloading up to the previous maximum strain.

RESULTS FROM EXPERIMENTS AND CALCULATIONS

Three sets of conditions were used for an experimental-theoretical comparison. These conditions were:

(1) Elastic-aluminum impact rod - elastic-aluminum test rod

(2) Elastic-aluminum impact rod - plastic-aluminum test rod

(3) Elastic-magnesium impact rod - plastic-aluminum test rod

The first case was that of the impact of two 7075-T6 rods at a velocity of such magnitude that the system remained elastic. In the experiment conducted, a 0.500-inch diameter and 12-inch long impacting rod struck a 0.500-inch diameter, 144-inch long test rod. The compression pulse was recorded 42 inches from the impacted end of the test rod as it first propagated down the rod and then again after it reflected from each end of the free-ended bar and passed the gage a second time after traveling 24 feet. Attenuation in this case amounted to less than 5 percent, and the dispersion, as can be seen from the oscilloscope trace in figure 7, was negligible. Figure 8 is the characteristic diagram for this case, while figure 9 compares the calculated stresses with the experimental data.

The second case considered was that of a 7075-T6 aluminum impacting rod striking a 7075-0 aluminum test rod at such a velocity that the impacting rod remained elastic while the test bar underwent plastic deformation. Figure 10 is the characteristic diagram for this case, and figure 11 is a plot of calculated and experimentally measured stresses at two points along the test bar.

The third case considered was for the impact of dissimilar metals. Here an aluminum test rod (7075-0) was impacted by a magnesium rod (ZK60A). The strengths of the rods and the impact velocity again were such that the impacting rod remained elastic while the test rod underwent plastic deformation. The magnesium was chosen because it has an impedance lower than that of aluminum so it rebounds after impact, producing the desired rectangular pulse. Figure 12 is the associated characteristic

diagram and figure 13 is a comparison plot of calculated and experimentally measured stresses at two points along the test rod.

ERROR ANALYSIS

The accuracy of the theoretical and experimental results presented here is greatly dependent on the accuracy and care with which the experimental data are gathered and reduced. The most important and critical piece of data is the stress-strain curve. As previously stated, the stress-strain curve used here was experimentally obtained in compression on a standard testing machine. The assumption was made that the material is not strain-rate sensitive. In the theoretical calculations, the slope of the curve must be used to obtain the velocity of each stress wave of different intensity (see fig. 4). A slight error in the slope of the stress-strain curve will thus cause an error in the distance down the rod a given stress level will be felt. The magnitude of the stress generated by a given impact velocity is also dependent on the stress-strain curve, but this quantity is not overly sensitive to error as it is a function of the area under the curve.

In the reduction of the experimental data, the stress-strain curve again plays a critical role as the desired value of stress must be obtained from the measured value of strain. The largest reading error will occur when the stress is relieved due to the large permanent set in the material. This results in a comparatively small change in strain when unloaded, relative to the change in strain when loaded beyond the elastic limit. Loading might thus be represented on a strain-time curve with a displacement of ten times that representing unloading. Thus a given oscilloscope trace reading error will result in a discrepancy ten times worse on the unloading wave than on the loading wave. This may result in poor agreement between calculated and experimental results, but fortunately is most serious only at the low stress levels which are not of primary interest.

DISCUSSION AND CONCLUSIONS

The major conclusion drawn from this study is that the one-dimensional analysis used here for both elastic and plastic wave propagation is quite good. The maximum error encountered in predicting the maximum stress of the incident pulse was less than 11.5 percent. Better agreement was found in predicting the speed of propagation in those tests involving only aluminum as may be seen in figures 9 and 11. However, significant

discrepancies in the speed of propagation were noted in those tests involving magnesium as may be seen in figure 13. For design purposes this method seems to be more than adequate as the inaccuracies are small compared with the unknowns for which allowance must be taken, such as material properties and loading.

A second conclusion drawn from the accuracy of the theory is that elastic stress waves can be used to cancel plastic waves. This principle might well be applied to the design of shock-mitigating devices.

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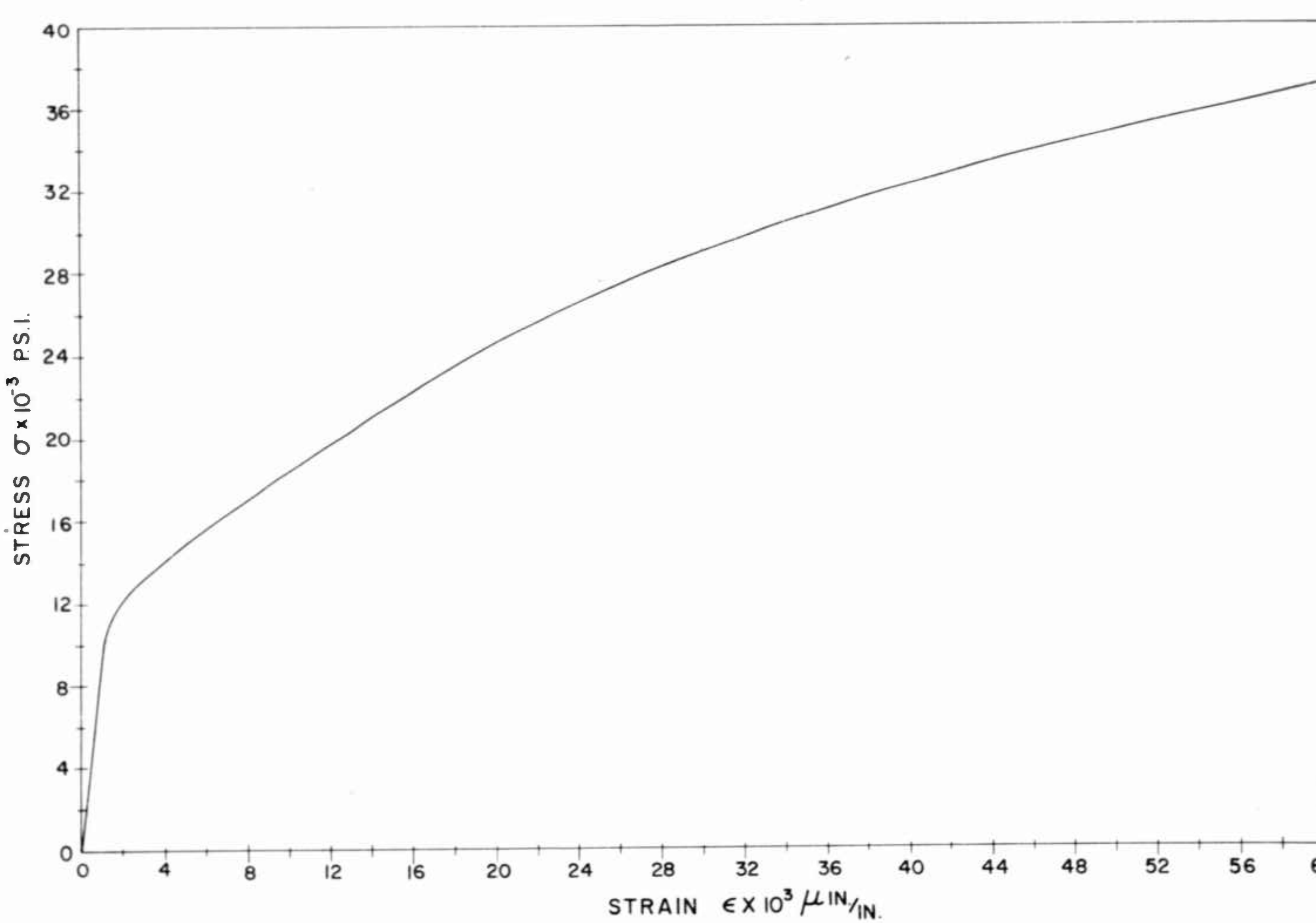


FIG. I COMPRESSION STRESS-STRAIN CURVE
7075-O ALUMINUM

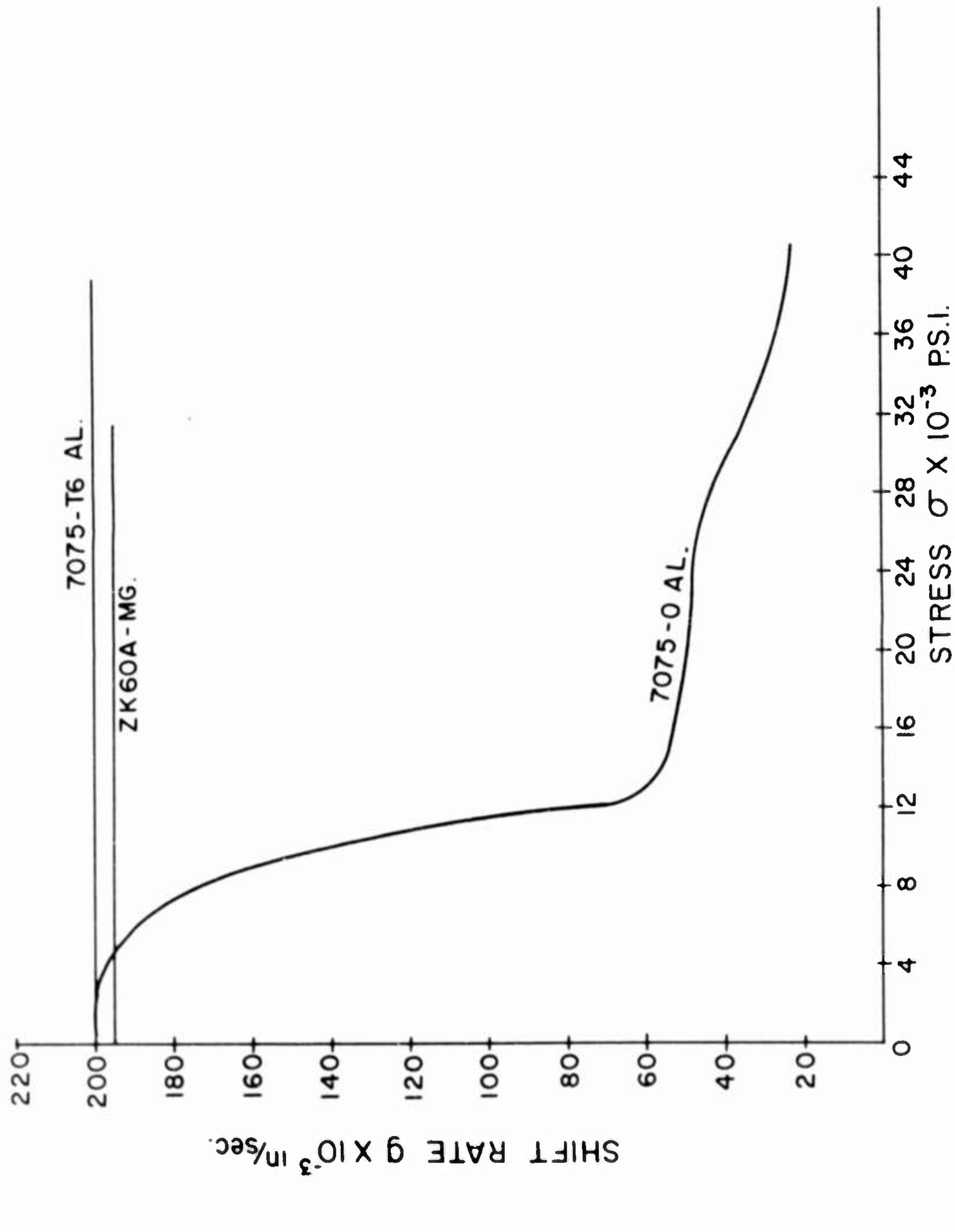


FIG. 2 SHIFT RATE VS STRESS

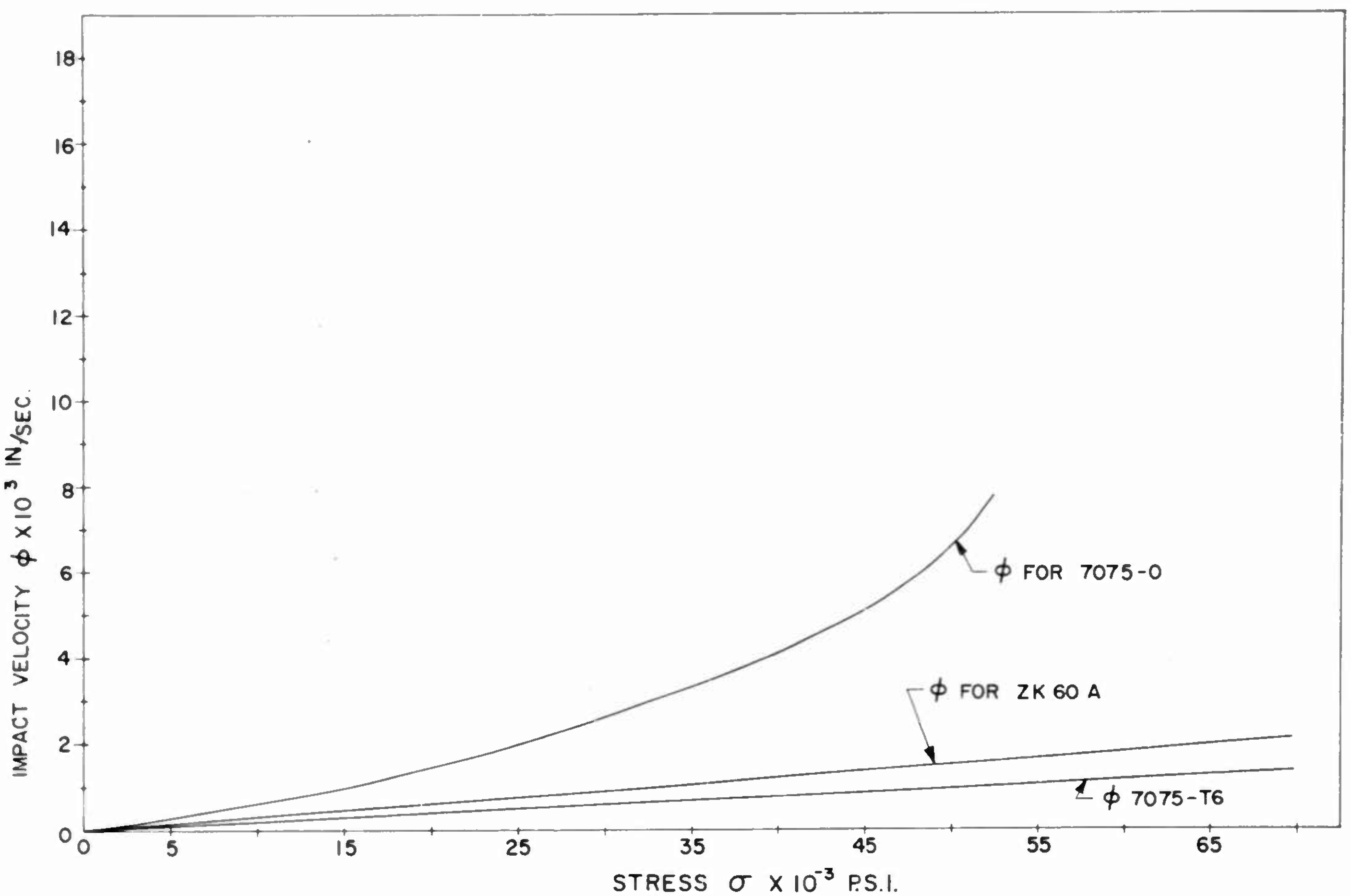


FIG. 3 IMPACT VELOCITY VS STRESS

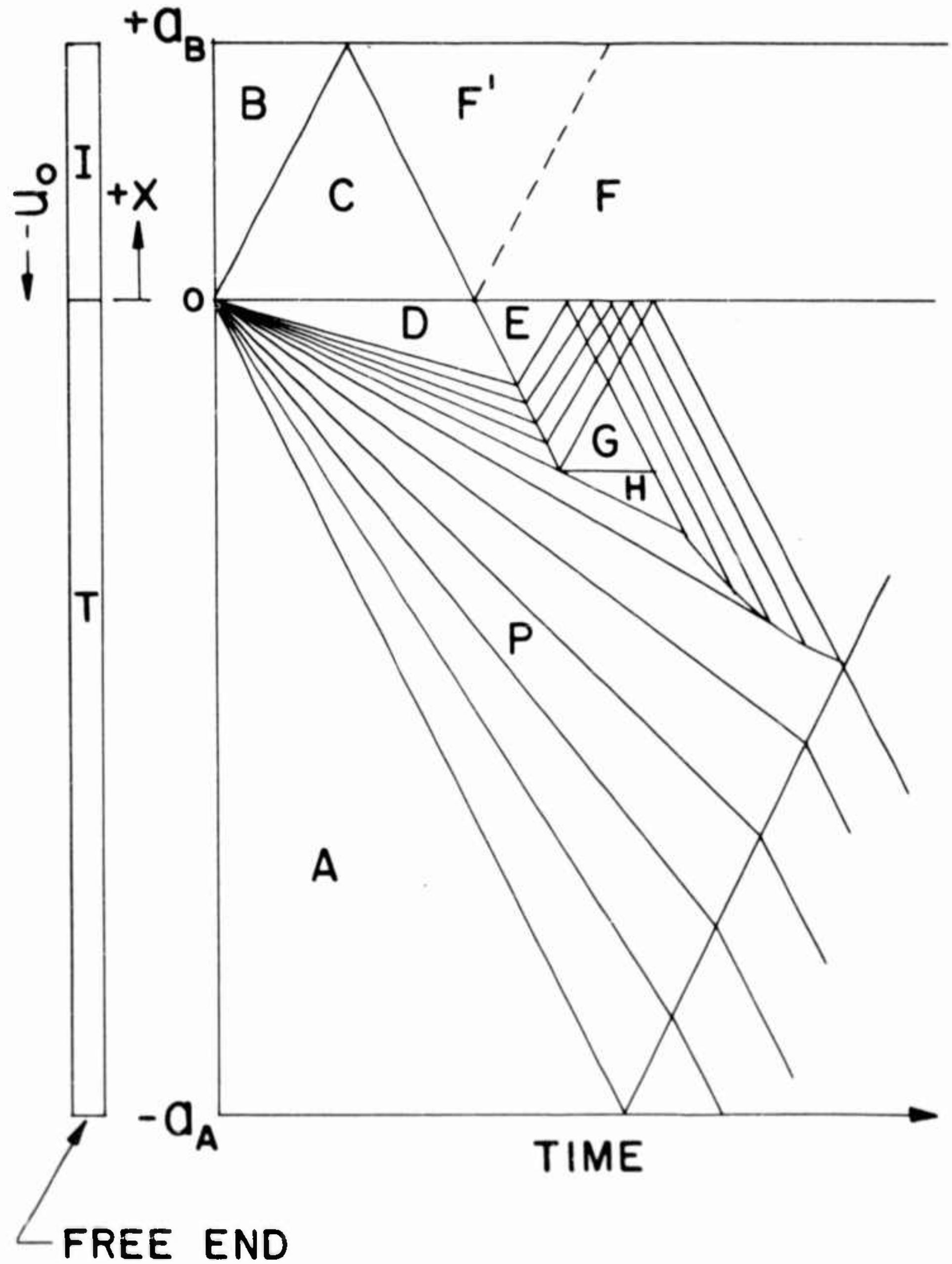


FIG. 4 CHARACTERISTIC DIAGRAM

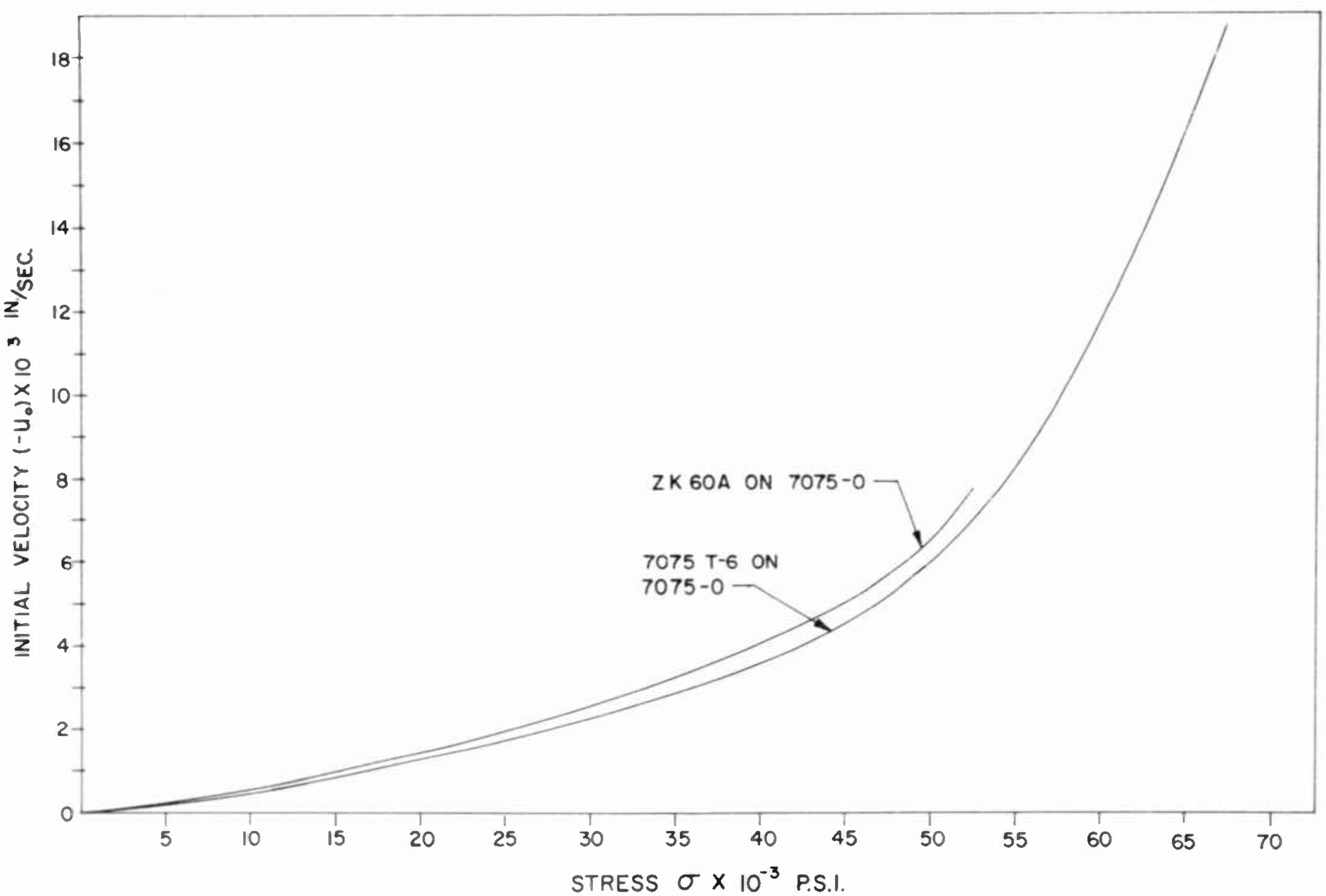


FIG. 5 VELOCITY OF IMPACT VS STRESS.

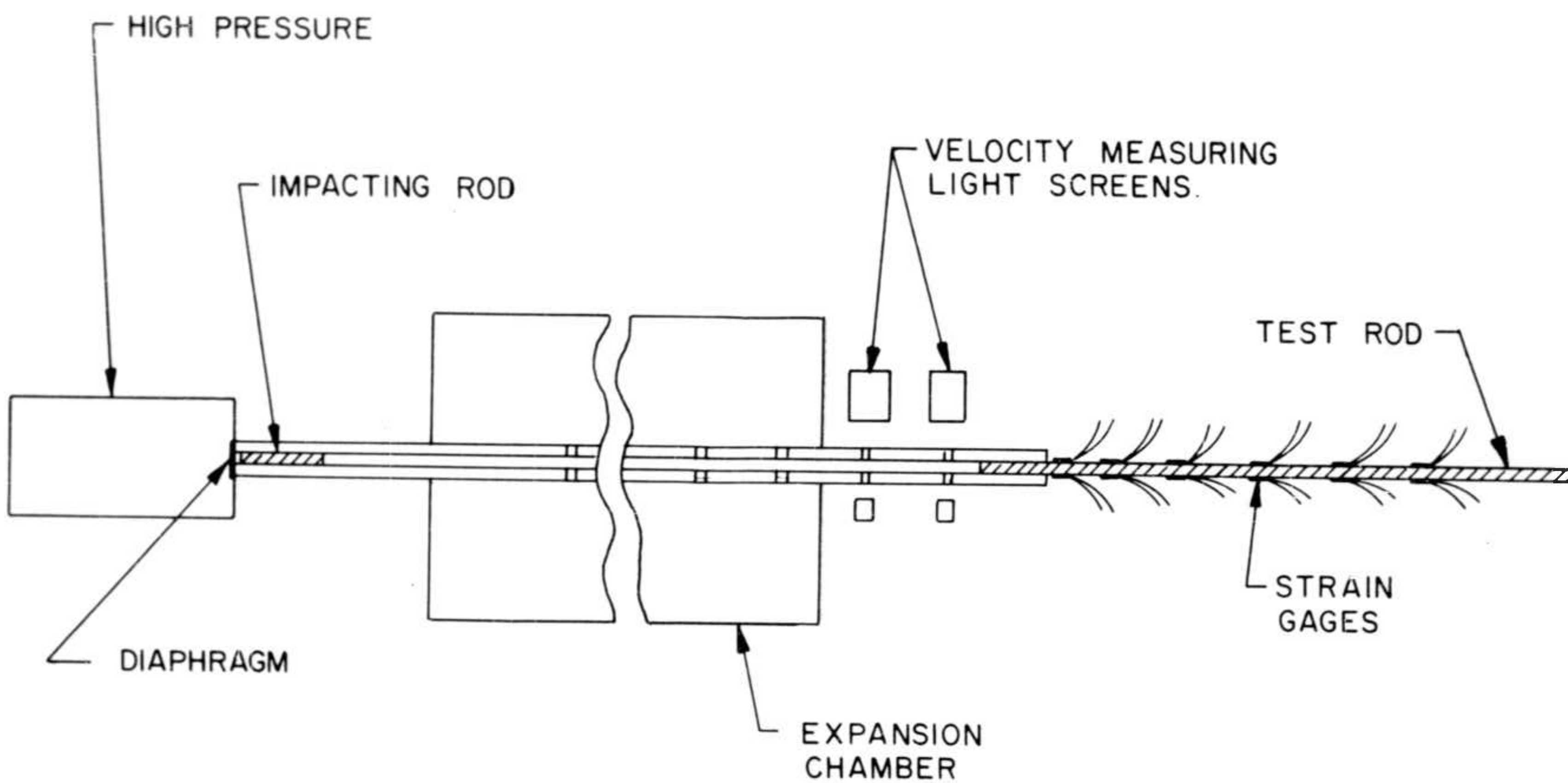


FIG. 6 TEST APPARATUS

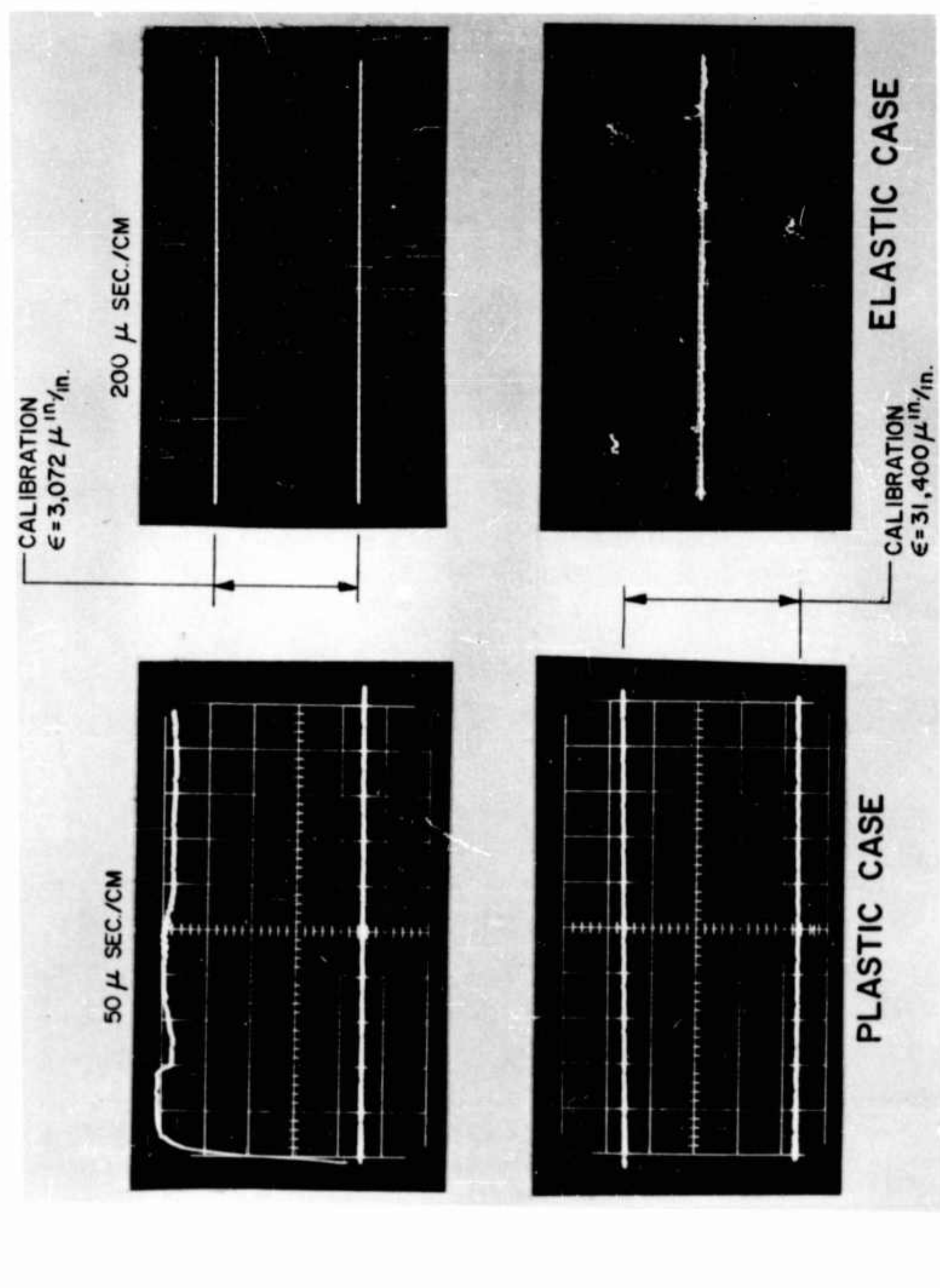


FIG. 7 STRAIN-TIME HISTORY AFTER IMPACT

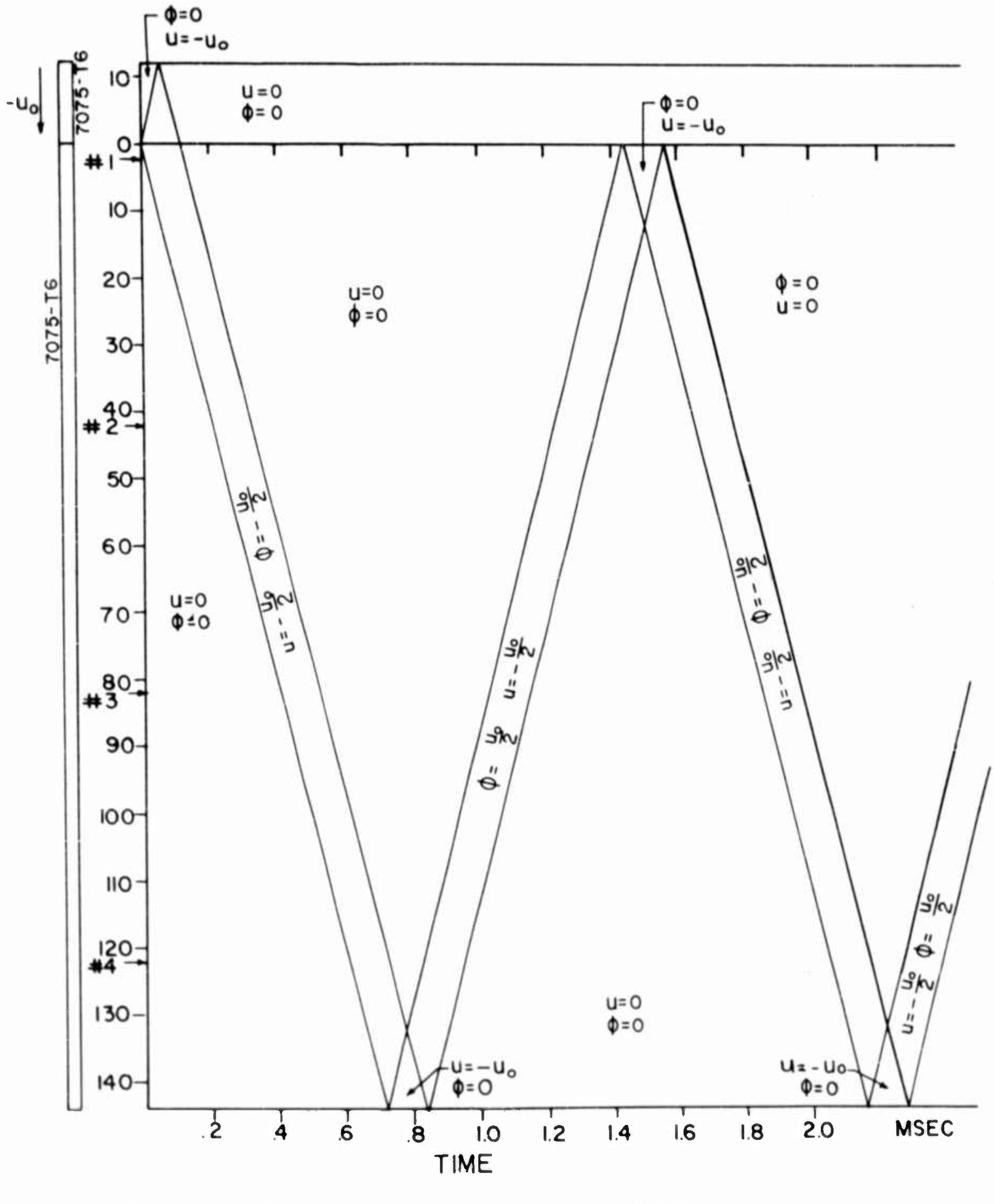


FIG. 8 CHARACTERISTIC DIAGRAM ALUMINUM (ELASTIC) IMPACTING ALUMINUM (ELASTIC)

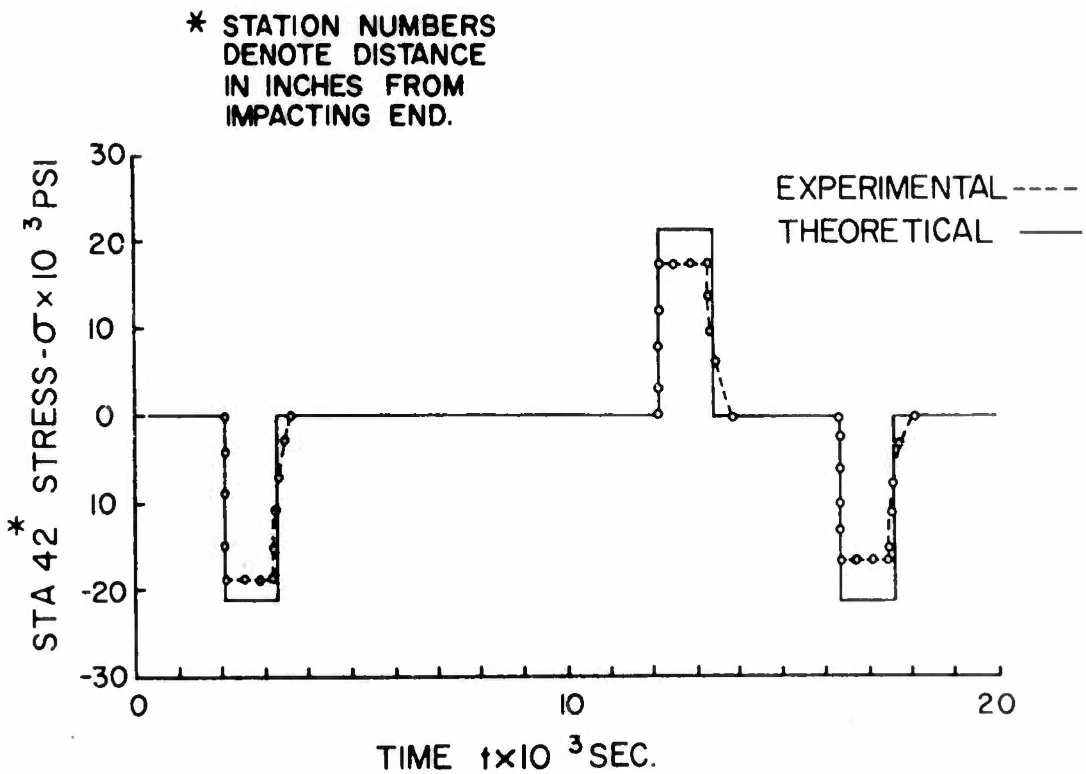


FIG. 9 THEORETICAL-EXPERIMENTAL COMPARISON OF ALUMINUM (ELASTIC) IMPACTING ALUMINUM (ELASTIC)

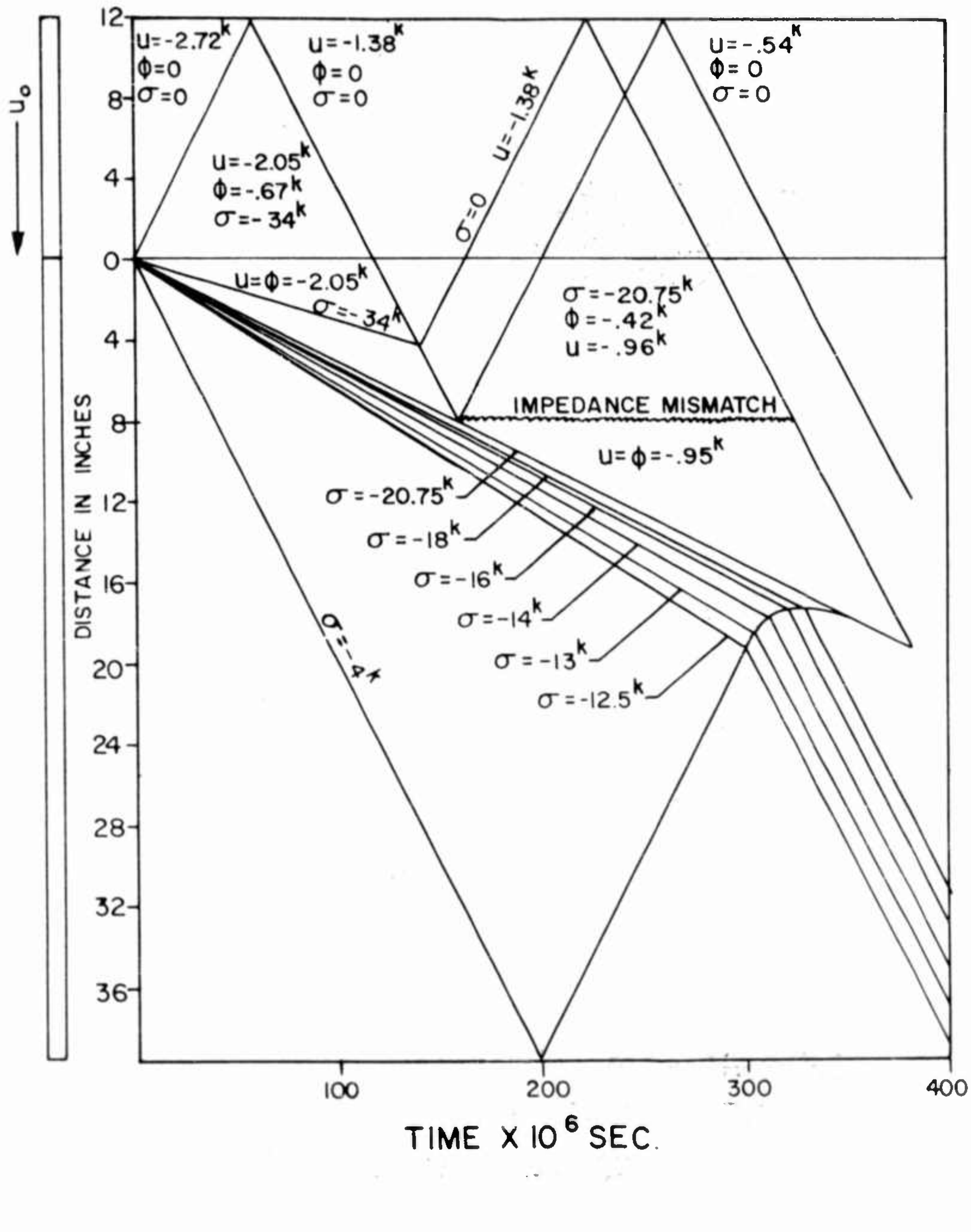
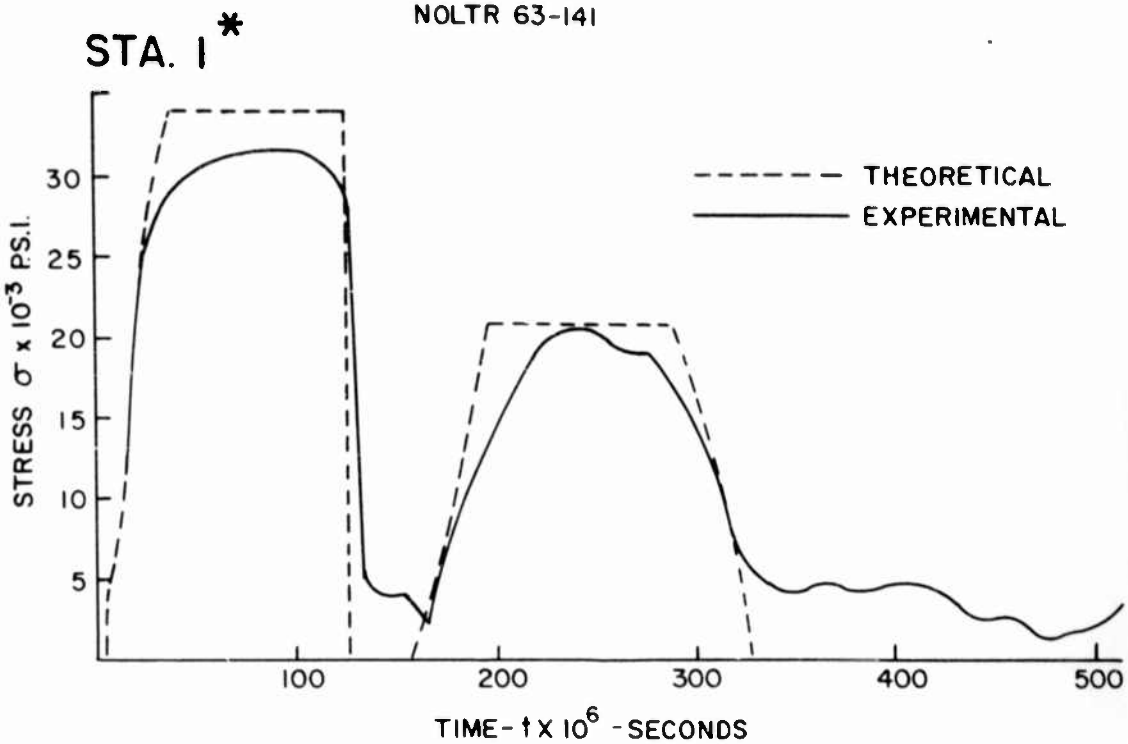


FIG. 10 CHARACTERISTIC DIAGRAM ALUMINUM (ELASTIC) IMPACTING ALUMINUM (PLASTIC)



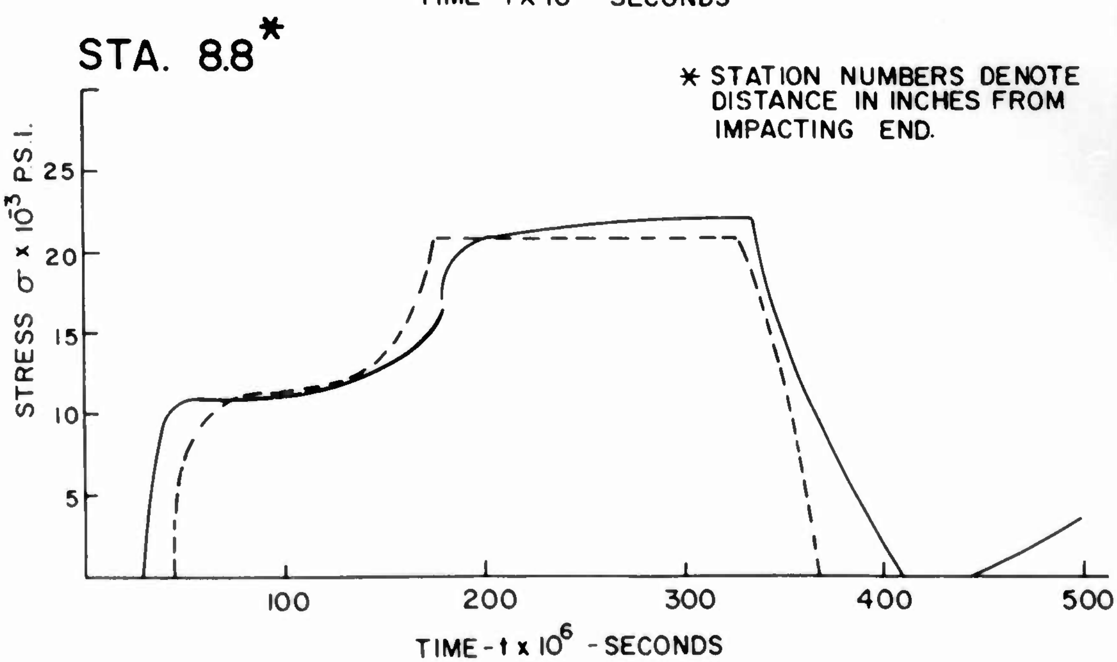


FIG. 11 THEORETICAL-EXPERIMENTAL COMPARISON OF ALUMINUM (ELASTIC) IMPACTING ALUMINUM (PLASTIC)

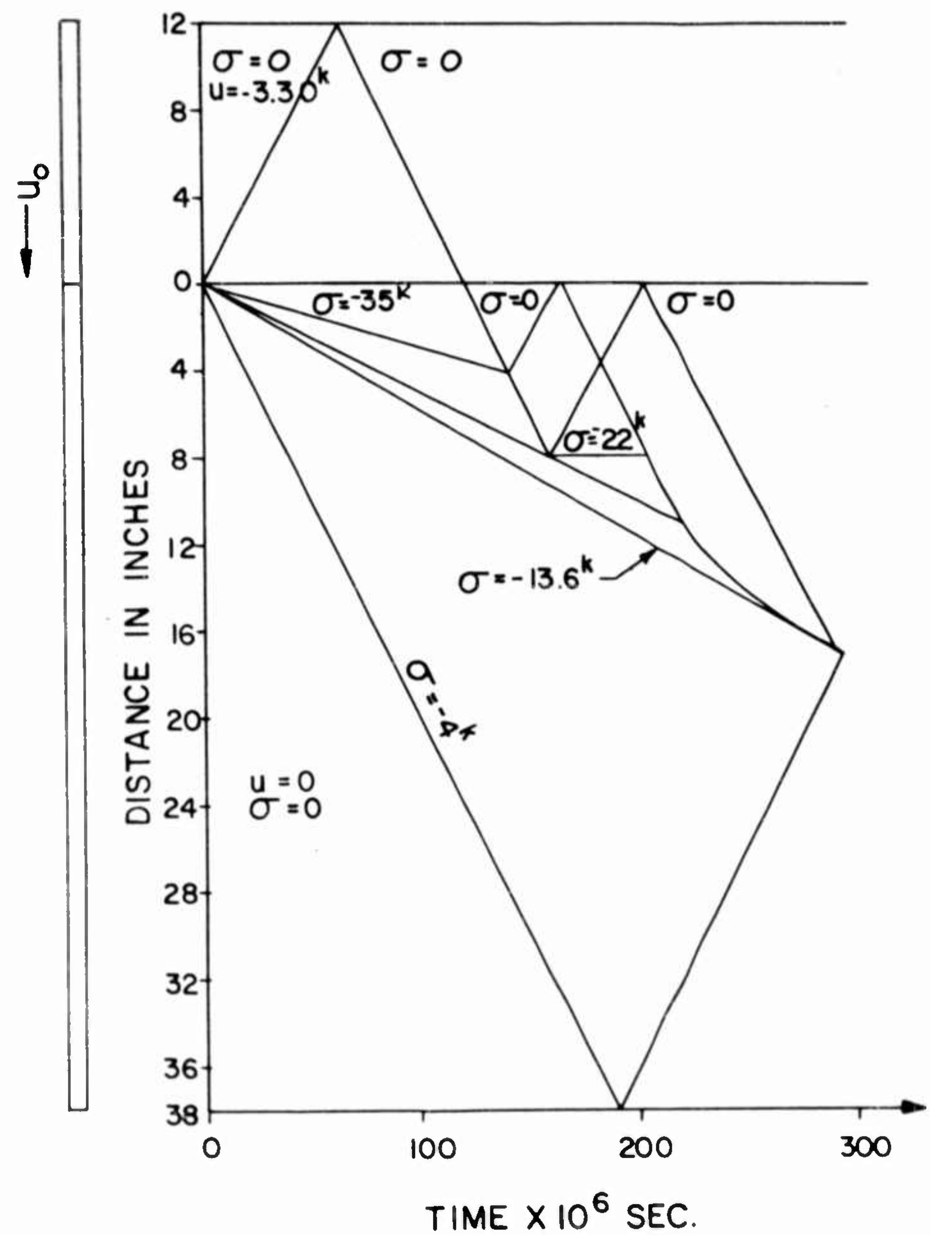
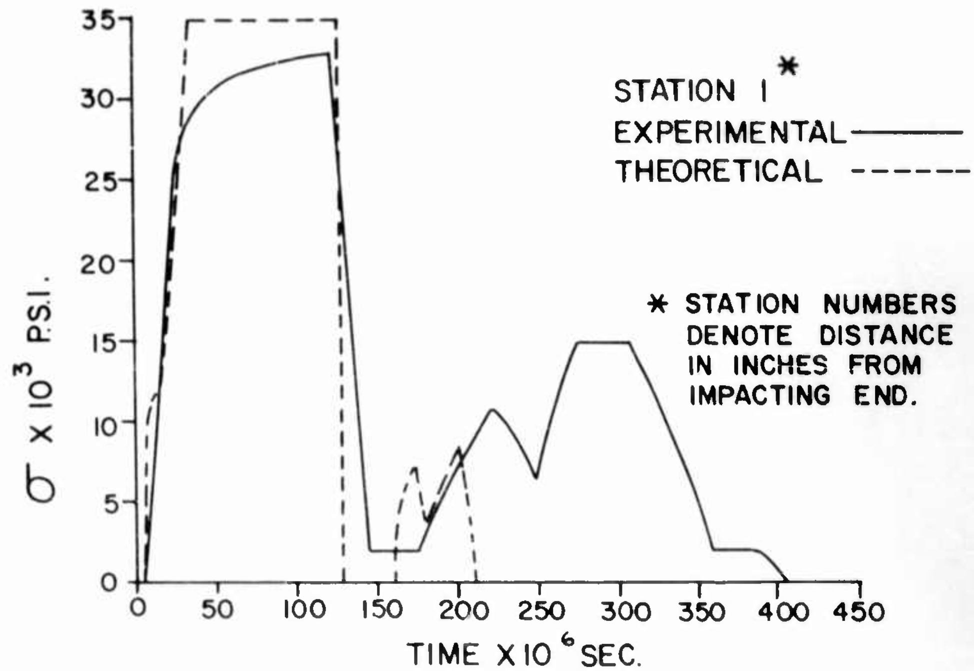


FIG. 12 CHARACTERISTIC DIAGRAM MAGNESIUM (ELASTIC) IMPACTING ALUMINUM (PLASTIC)



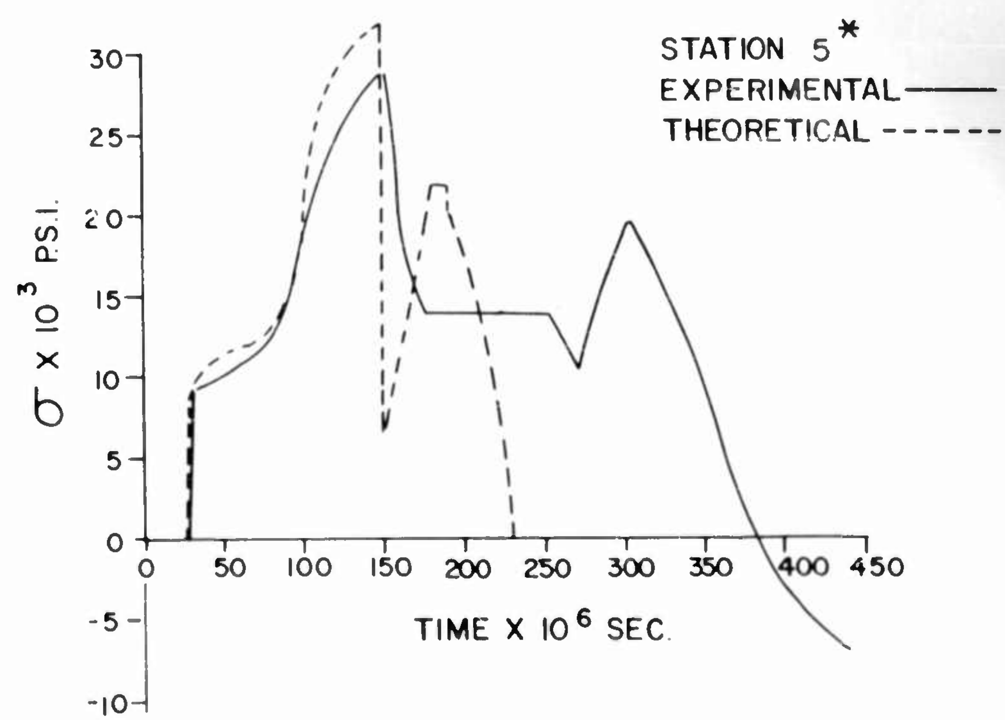


FIG. 13 THEORETICAL- EXPERIMENTAL COMPARISON OF MAGNESIUM (ELASTIC) IMPACTING ALUMINUM (PLASTIC)

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SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Shock wave	SHWV	Acceleration	ACCL		
Stress	STRS	Equipment	EQUI		
Propagation	PROO	Impact	IMPC		
Aluminum	ALUM	High speed	HIGS		
One-dimensional	ONED	Strain	STRN		
Theories	THEY	Experiments	EXPE		
Three-dimensional	THRD	Ballistics	BALS		
Elasticity	ELAS	Physics	PHYS		
Plasticity	PLSY	Shock	SHOC		
Air	AIRE	Testing	TEST		
Gun	GUNS				
Rod	RODS				

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Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-141)
STRESS-WAVE PROPAGATION IN ALUMINUM (U), by R. H. Waser and others. 31 July 1963. 10p. illus., tables. (Ballistics research report 107) BuWeps task PR-13. UNCLASSIFIED

The one-dimensional theory of stress-wave propagation has been found to adequately represent a three dimensional experimental situation in both the elastic and plastic regimes. An air gun was used to accelerate a rod and impact it against a stationary test rod to produce a force pulse. The strain resulting from this pulse was recorded at various positions along the test rod. The deviation between the theoretical and experimental values of maximum stress was less than 11.5 percent.

1. Shock waves - Propagation
2. Aluminum - Shock effects
3. Metals - Elasticity
4. Metals - Plasticity
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